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Changes in Vegetation and Rainfall over West Africa during the Last Three Decades (1981-2010)

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Abstract

The decadal variability of rainfall and vegetation over West Africa have been studied over the last three decades, 1981-1990, 1991-2000 and 2001-2010 denoted as 1980s, 1990s and 2000s, respectively. Climate Research Unit (CRU) monthly precipitation and Normalized Difference Vegetation Index (NDVI) from the National Oceanic and Atmosphere Administration (NOAA), all covering the period 1981-2010 have been used. This study aimed to assess the changes in the land surface condition and the spatio-temporal distribution of rainfall over West Africa region. The relationship between rainfall and vegetation indices over this region was determined using Pearson's correlation. Also, the decadal comparison between rainfall and NDVI over the region was based on the significant t-test and the Pearson's correlation. Results showed that significant return to wet conditions is observed between decade 1980s and decade 1990s over West Africa, and also during decade 2000s with the exception of central Benin and the western Nigeria. Meanwhile, a regreening of the central Sahel and Sudano-Sahel regions is noted. From 1990s to 2000s, this regreening belt is located in the South and the coastal areas: the Guinea Coast, Sudano-Guinea and western Sahel regions. A northward displacement of this re-greening belt is also detected. Thus, a linear relationship occurs between rainfall and NDVI in the Sudanian savannah region, but it is not the case in the rest of West Africa. This may suggest that the re-growth of vegetation in the Sudanian savannah region may be linked to rainfall supplies. Therefore, re-greening over Sahel region in

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1990s is related to rainfall recovery. However, this re-greening was not sustained in the decade 2000s due to a slight decrease in rainfall.

Keywords

Decadal Variability, NDVI, Re-Greening, Rainfall Recovery, Significant *t*-Test

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1. Introduction

In many regions of West Africa, the land surface has faced considerable stress over decades. In view of the importance of land surface conditions in the water cycle, many researchers have focused on the relationship between rainfall and vegetation, especially in semiarid environments [1]. For example, Charney [2] first linked the Sahel drought of the 1970s and 1980s to changes in the land surface conditions: Land degradation induced by human activities contributes to increase the surface albedo. This change in surface albedo is associated with a cooling at the surface (due to a loss of energy) compensated by an adiabatic subsidence (heating). This reaction in the atmospheric dynamic is unfavourable to the convection and, therefore, reduces rainfall which acts to stress the vegetation cover. Then, this decrease in the vegetation cover is likely to increase the surface albedo contributing to long-term drought conditions maintenance over Sahel through a positive feedback cycle. Moreover, other studies, such as [1] and [3] linked this drought to anthropogenic land use changes. Fensholt and Rasmussen [4] have shown that vegetation is mainly influenced by rainfall in semiarid areas, *i.e.*, where annual rainfall amount is around 150 mm·yr^{-1}. The regional rainfall variability has a strong seasonal link with convection processes [5]-[7] and the thermal gradient between the ocean and the continent [8]. Many research programmes are held over West Africa these last years in order to enhance the knowledge about the West African Monsoon (WAM). Among them, we have the African Monsoon Multidisciplinary Analysis (AMMA) and the West African Science Service Center for Climate Change and Adapted Land Use (WASCAL). The importance of atmosphere, land, and ocean processes is emphasized in field experiments such as the AMMA international program [9]-[12]. Nowadays, some results have brought out the re-greening of the vegetation over some parts of West African region [13] [14]. This study aims to examine the time-evolution of vegetation and rainfall over West Africa during the last three decades using the Normalized Difference Vegetation Index (NDVI) from the National Oceanic and Atmospheric Administration (NOAA), Advanced Very High Resolution Radiometer (AHVRR) [15] and rainfall from the gridded Climate Research Unit (CRU) data covering the period 1981-2010. The paper is organised as follow: in Section 2, we first of all introduce the study area, followed by the data and method. Then, in Section 3, we present the results and discussion. And in final, the conclusion is presented in Section 4.

2. Study Area and Data

2.1. Presentation of the Study Area

Figure 1 shows the study area located between the equator and 20˚N for latitudes, and between 20˚W and 15˚E for longitudes. The mean annual rainfall over the period 1971-2000 is represented using isohyets from 400 mm·yr^{-1} (Sahel region) to 2000 mm·yr^{-1} (Guinea Coast). The mean vegetation cover over West Africa is showed in shaded areas and is derived from the NDVI climatology between 1981 and 2010. The vegetation of West Africa presents a simple picture compared to other part of tropical Africa [16]. The zones of vegetation are principally related to rainfall-based climatic zones and the nature of the soil. This results in a couple of vegetation zone superimposed from the southern Guinea coast, which experiences rainfall throughout the year, to northern regions with of increasingly drier vegetation up to the Sahara desert. As for rainfall, the vegetation distribution over West Africa follows a latitudinal gradient. This is illustrated from North to South by the contrast between desert in the North, Sudanian savannah or woody savannah zone in the middle, and tall grasses, scattered trees and shrubs and forest zone over Guinean coastal regions (a tropical-humid zone with a rich variety of forests).West African rainfall is principally related to seasonal shifts in the pressure over the Sahara, which determine the location of the Inter-Tropical Convergence Zone (ITCZ; [17] [18]), where organised deep convec-

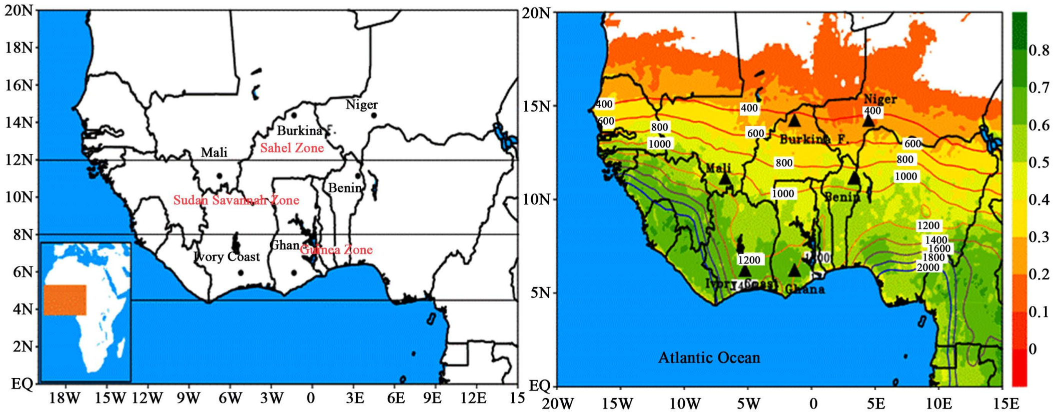


Figure 1. Study area showing the three climatic zone (right) and the mean annual rainfall climatology (in contour) and NDVI climatology (in shaded) 1981-2010 (left).

tive systems, *i.e.*, mesoscale convective systems, associated with 80% of Sahel rainfall develop [7]. During summer, the low pressure over the Sahara lies between the North-East trades, or hamattan, and the humid South-West Monsoon flow. It is the Sahel rainy season [19] [20]. During the boreal winter, such a pattern is reversed due to high pressure anomalies over the Sahara. The ITCZ moves southward and penetrate into the southern hemisphere.

2.2. Data

2.2.1. Rainfall Data

The gridded rainfall dataset from Climate Research Unit (CRU) version TS3.10.1, which presents a larger time cover with a wide spatial representation over West Africa, has been used for the study. This data is composed of 1224 observational grid-points for the 1901-2009 periods with 0.5 × 0.5 degree resolution. The precipitation data have been compiled by the CRU over the last 20 years [21] [22]. The original data have been subjected to comprehensive quality control over the years. Updates for more recent years and additional station data collated by the CRU have also been checked for homogeneity and outliers. The correction of individual records requires detailed local meteorological and station meteorological information, which are not readily available [23].

2.2.2. NDVI Data

The vegetation indices implanted for this study is the National Aeronautical and Space Administration (NASA) AVHRR NDVI, covering the period 1981-2012 with horizontal resolution of 8 km and 15-day temporal frequency. It is derived from NOAA satellites, and processed by the Global Inventory Monitoring and Modeling Studies group (GIMMS; [24]-[26]) at the NASA. Spectral vegetation indices are usually composed of red and near-infrared radiances or reflectance [27]. According to [28], these indices are one of the most widely used remote sensing measurements. They are highly correlated to the photosynthetically active biomass, chlorophyll abundance, and energy absorption [29]. The use of spectral vegetation indices derived from AVHRR satellite data followed the launch of NOAA-6 in June 1979 and NOAA-7 in July 1981 [30]. The AVHRR instruments on NOAA-6 and NOAA-7 were the first in the TIROS-N series of satellites to have non-overlapping channel 1 and channel 2 spectral bands. Overlapping red and near infrared spectral bands precludes calculating a NDVI. The NDVI is calculated as NDVI5 (channel 2 − channel 1)/(channel 2 + channel 1) (Tucker, 2005). The NDVI has become the most used product derived from NOAA AVHRR data [28], largely from the use of NDVI datasets formed via maximum value compositing [31]. The latest version, termed the third generation NDVI data set (GIMMS NDVI3g) has been recently produced for the period July 1981 to December 2011 with AVHRR sensor data from NOAA 7 to 18 satellites [24].

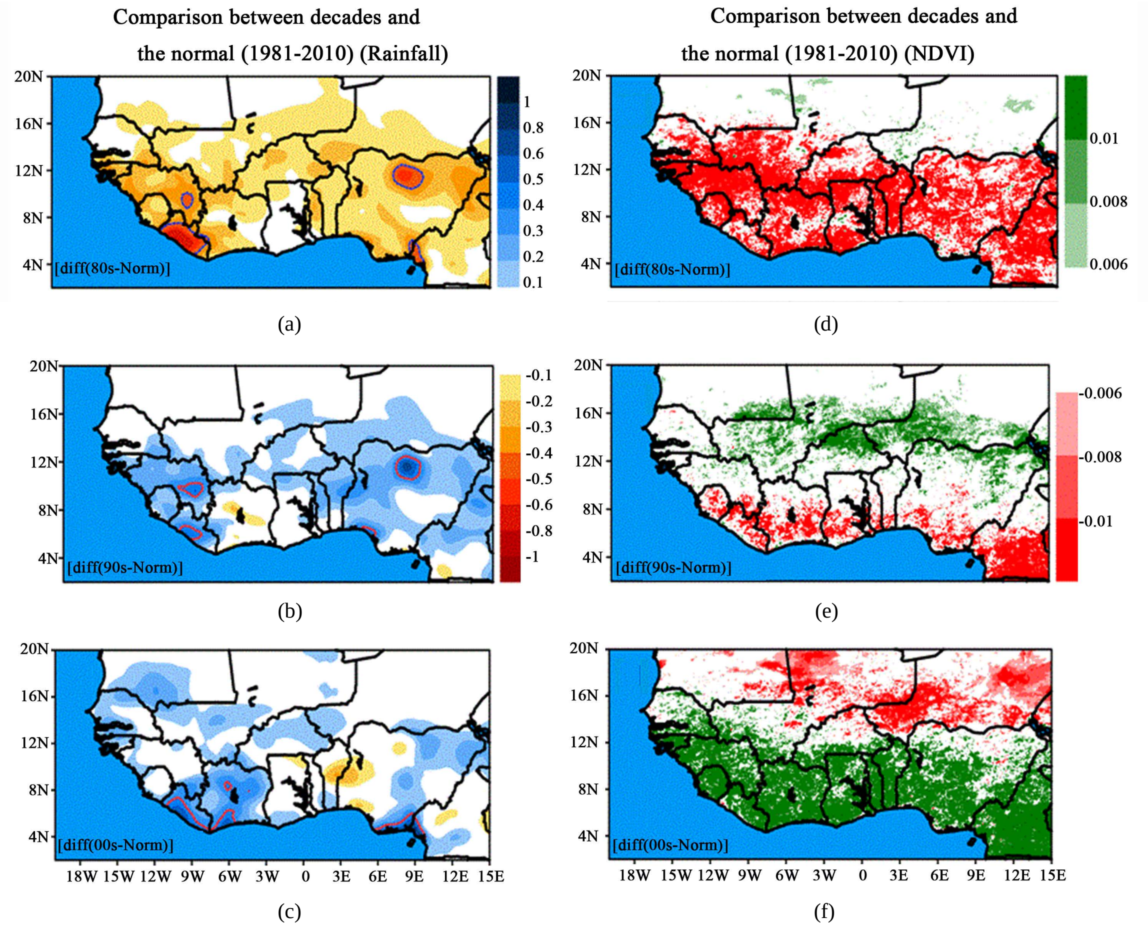
2.3. Methodology

Significance of differences between the three different decades (1980s, 1990s and 2000s) is computed using a two-sided *t*-test. The *p*-value is a numerical measure of the statistical significance of a hypothesis test. The monthly data are considered for the analysis so 120 months/decade. It tells us how likely it is that we could have gotten our sample data (e.g., 10 year measurements of rainfall and NDVI) even if the null hypothesis is true (e.g., changes in rainfall and vegetation is significant). The significance level 5% so if the p-value is less than 5% ($p < 0.05$), we conclude that the null hypothesis can be rejected (*i.e.*, no significant change in rainfall or vegetation). In other words, when $p < 0.05$ it is noted that the results are statistically significant, meaning that strong evidence of change in rainfall and vegetation is noted between two considered decades. Also the relationship between rainfall and vegetation during the three decades is determined based on Pearson's correlation (the equations are not shown in this paper).

3. Results and Discussion

3.1. Decadal Changes in Rainfall and NDVI

The comparisons between each decade and the normal conditions (*i.e.*, the average for the1981-2010 period) of rainfall and NDVI are displayed in **Figure 2**. 1980s is drier than the normal conditions. A rainfall deficit is identified in most of the West African region, but this only significant in northern Nigeria, Liberia and southern Guinea (**Figure 2(a)**). The decade 1990s is wet compare to the normal conditions significant increases of rainfall occur in northern Nigeria, Liberia and southern Guinea (**Figure 2(b)**). In the decade 2000s, rainfall increased in Liberia and Cote d'Ivoire, whereas it slightly and non-significantly decreasing over Guinea regions, such as in Benin and Nigeria (**Figure 2(c)**).



(a) (d)

(b) (e)

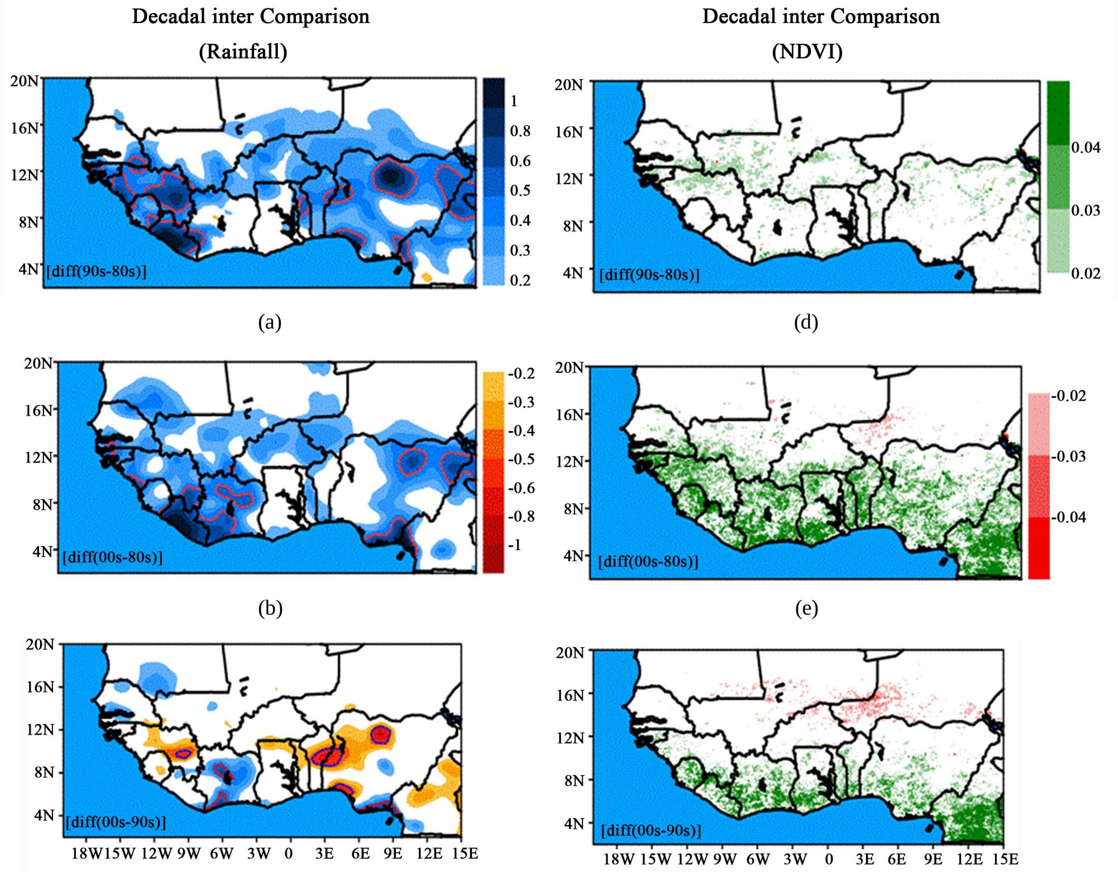
(c) (f)

Figure 2. Spatial distribution of changes in annual rainfall mean ((a)-(c)) and NDVI ((d)-(f)) over West Africa in the 1980s, 1990s and 2000s compare to normal conditions (*i.e.*, the 1981-2010 period). Contours lines indicate the significant difference at $p = 0.05$ as determined by two-sided *t*-test.

Compare to normal conditions, the NDVI is negative in most of the West African regions in the decade 1980s. That is particularly evident in Guinea and Sudanian Savannah regions. However, some specific areas with positive greenness are observed over central Ghana and Cote d'Ivoire (**Figure 2(a)**). In the decade 1990s, a re-greening is observed in central West African region and in West Sudanian Savannah region (between 12˚N and 16˚N). Meanwhile, anomalies of vegetation cover remain negative over the Gulf of Guinea coastal regions (**Figure 2(b)**). In the decade 2000s, a re-greening occurs over Gulf of Guinea coastal regions, the Sudanian Savannah regions and the western Sahel. The re-greening has therefore extended to the coastal region, which indicates that a re-greening trend is progressing southward and westward (**Figure 2(c)**).

According to earlier studies, 1980s is the driest decade of the century in the West African region [10] [32]-[35]. However, a rainfall recovery in the 1990s was reported in many regions [36]-[38]. This recovery was limited in the decade 2000s over some regions, such as southern Guinea and Cote d'Ivoire.

Rainfall time-evolution from decade to decade has been investigated using a *t*-test at $p = 0.05$ (**Figure 3**). **Figure 3(a)** shows the difference in annual rainfall average between the 1990s and 1980s. Positive changes, which can be greater than 300 mm·yr^{-1}) is identified in most of West African regions. This is significant over the southernmost and northernmost regions of Nigeria, Liberia, Guinea and south-western Senegal. **Figure 3(b)** shows the differences in annual rainfall between 2000s and 1980s, 2000s are also wetter than 1980s in most of West Africa, with the exception of few regions in Ghana and Benin where rainfall is decreasing (**Figure 3(b)**). **Figure 3(c)** shows the difference between 2000s and 1990s. 2000s thus appear to be significantly wetter than the 1990s in some specific regions, such as Cote d'Ivoire. However, 2000s are usually dryer than 1990s in Nigeria, Benin, Togo, Ghana and Guinea.



(a) (d)

(b) (e)

(c) (f)

Figure 3. Inter-comparison of changes (95% level) in rainfall ((a)-(c)) and NDVI ((d)-(f)) over West Africa between the1980s, 1990s and 2000s; Contours lines indicate the significant difference at $p = 0.1$ as determined by two-sided *t*-test.

The difference in vegetation cover between 1990s and 1980s shows a positive increase over Sudanian Savannah region of West Africa from 8˚N to 16˚N (**Figure 3(a)**). 2000s also appear greener than the decade 1980s from the Gulf of Guinea coastal regions to the Sahel regions (between 12˚N to 16˚N; **Figure 3(b)**). According to the comparison between 2000s and 1990s, the re-greening only persists along the Gulf of Guinea coastal regions (below 8˚N; **Figure 3(c)**).

After the droughts in 1980s, a re-greening is first identified in the Sudanian Savannah (between 8˚N and 15˚N) during 1990s. This re-greening could be related to enhancing rainfall over this region during the same period. This is not identified over the Gulf of Guinea coastal regions during 1990s, which does not show significant changes in the vegetation cover at this period. Such influence of annual rainfall on the re-greening of the Gulf of Guinea coastal regions could however be involved during 2000s.

In the Gulf of Guinea coastal region, the re-greening is more important than in the rest of West Africa. A decrease in vegetation cover is observed over Sahel region, area, in particular over Niger, Mali and Burkina. Over the Gulf of Guinea coastal region, which is principally covered by forest, a significant re-greening over the last two decades was noted, but statistically weak associated with changes in annual rainfall amounts. This finding is consistent with [39], who highlighted low sensitivity of the NDVI to rainfall variability over coastal regions, mountain regions and flooded areas. They concluded that the interannual variability of the rainfall does not have a significant effect on the photosynthetic activity.

In the decade 2000s, a re-greening is identified from the sudano-sahel to Gulf of Guinea coastal regions, while the vegetation cover is decreasing over the Sahel regions. This suggests a southward shift in the re-greening belt. Using the same data sets, Anyamba and Tucker [40] propose that a gradual return to dry conditions over the Sahel. Even though wet conditions remains over the Sahel during 2000s.

3.2. Relationship between Rainfall and NDVI over West Africa

The correlation between rainfall and NDVI is significantly positive (≥0.6) between 8˚N and 17˚N, *i.e.*, in the Sahel regions (**Figure 4**). In the decade 1980s, this correlation is about 0.8 in Guinea, Senegal and southern Mali

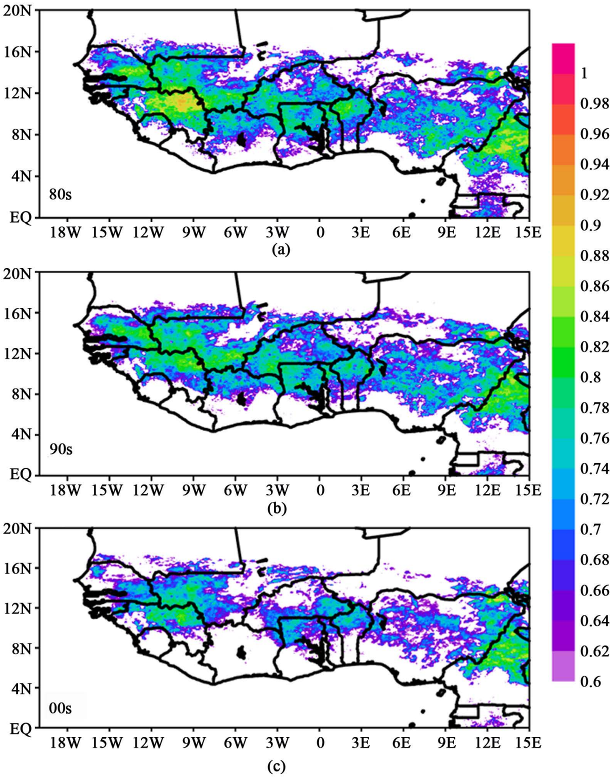


Figure 4. Spatial correlation between NDVI and rainfall over (a) decade 1980s; (b) decade 1990s and (c) decade 2000 s significance areas at $p = 0.05$.

(**Figure 4(a)**). It is however weak over Gulf of Guinea coastal regions from Sierra Leone to Nigeria (correlation ≤ 0.4). This is explained by the presence of forest and the high annual rainfall amount in these regions. It is shown that correlation between rainfall and vegetation decreases with the increase in precipitation [41] [42]. Similar results are found in the decade 1990s, but the correlation values are slightly reduced (**Figure 4(b)**). Slight enlargement of the zone with weak correlation values northward apart from the coastal region up to sub-Sudanian Savannah regions have been noted during this period. In the decade 2000s, the area with high positive correlation has shrunk with an accentuation of northward expansion of the area with weak values over Sudanian Savannah region (**Figure 4(c)**). Thus, the area with high correlation kept dropping all over the region but precisely over Republic of Guinea, Mali and Senegal during the three decades. This suggests that in general the vegetation growing is controlled by rainfall availability over the region.

3.3. Intra Seasonal Variability Case Studies

Different metrics related to rainfall and NDVI along different regions of West Africa are given in **Table 1**. The interannual variability over Guinea region is the highest in term of both rainfall and NDVI compare to Sahel and Sudanian savannah, where the rainfall and NDVI are the most correlated 0.56 (Niger) and 0.58 (Burkina). The correlation is weak over the Sudanian Savannah region, over Mali and Benin sites. This insignificant correlation could be due to time-lag between rainfall and vegetation growing, which is not always systematically as it is assumed in this work. The rainfall seasonal fluctuations could be responsible for the strong variability of NDVI over Guinea region where the region is characterised by two rainy seasons and two dry seasons. Also the land cover type is an important factor to [43] who found an average of 0.85 for grassland and 0.79 for forest.

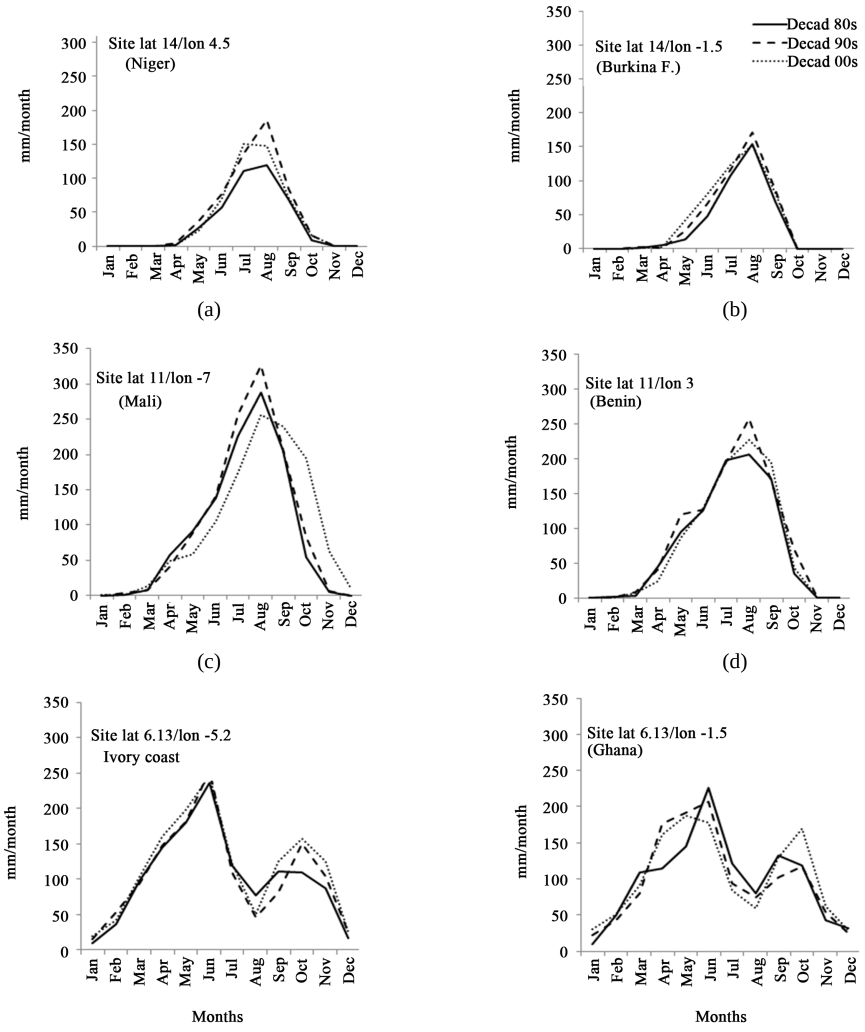
The intra annual variability of the rainfall at the six selected sites over the three main climatic zones of West African region is differently observed.

The selected sites over Sahel region are on latitude 14˚N and are located in Niger (**Figure 5(a)**) and Burkina Faso (**Figure 5(b)**). The rainfall regime is unimodal with the peak in August. Over the two Sahel sites the difference between the three decades is mainly observed at Niger site with 1990s as the rainiest (about 200 mm in August) and 1980s the driest (about 100 mm in August). This finding is in agreement with Hagos and Cook [44]. At Burkina Faso site the visual analysis does not show considerable changes. Over Sudanian savannah region the rainfall regime is still unimodal with the peak in August 350 mm and 250 mm respectively in Mali and Benin. But the rainfall amount is higher than the rainfall in Sahel. The important change noted was the shift of the rainy period during the last decade at Mali site (**Figure 5(c)**). This is due to a late onset and late secession of the rainfall and less precipitation in the core of the rainy season which is in agreement with Louvet et *al.* [45] finding. In Benin the rainy period did not change only some slight change has been observed in rainfall amount in August (**Figure 5(d)**). At last the two selected sites over Guinea regions Cote d'Ivoire (**Figure 5(e)**) and Ghana (**Figure 5(f)**) show a bimodal regime of the rainfall. The two peaks of rainfall are obtained respectively in May-June and October due to the presence of two rainy seasons. Detailed description of this regime can be found in Konaté and Kampmann [16]. The change occurs in the second rainy season with and an increase in the rainfall over the last decade. However many studies and research programmes (AMMA, WASCAL) built up over West Africa have shown the deep implications of the monsoon in the rainfall amount and spatial distribution over the West African region [35] [46] [47].

Table 1. Descriptive statistics for the rainfall and NDVI time series.

		Rainfall		**NDVI**		
Sites		Mean	STD.	Mean	STD.	Correlation
Sahel	Niger site	469.76	117.04	0.24	0.012	0.56**
	Burkina site	595.48	123.49	0.33	0.018	0.58**
Sudan Savannah	Mali site	1126.6	136.47	0.50	0.016	0.24
	Benin site	923.54	119.88	0.49	0.018	0.21
G-Guinea	Cote d'Ivoire site	1244.4	181.37	0.63	0.036	0.45*
	Ghana site	1198.3	141.25	0.63	0.040	0.40*

**Correlation is significant at $p = 0.01$; *Correlation is significant at $p = 0.05$.



(a) (b)

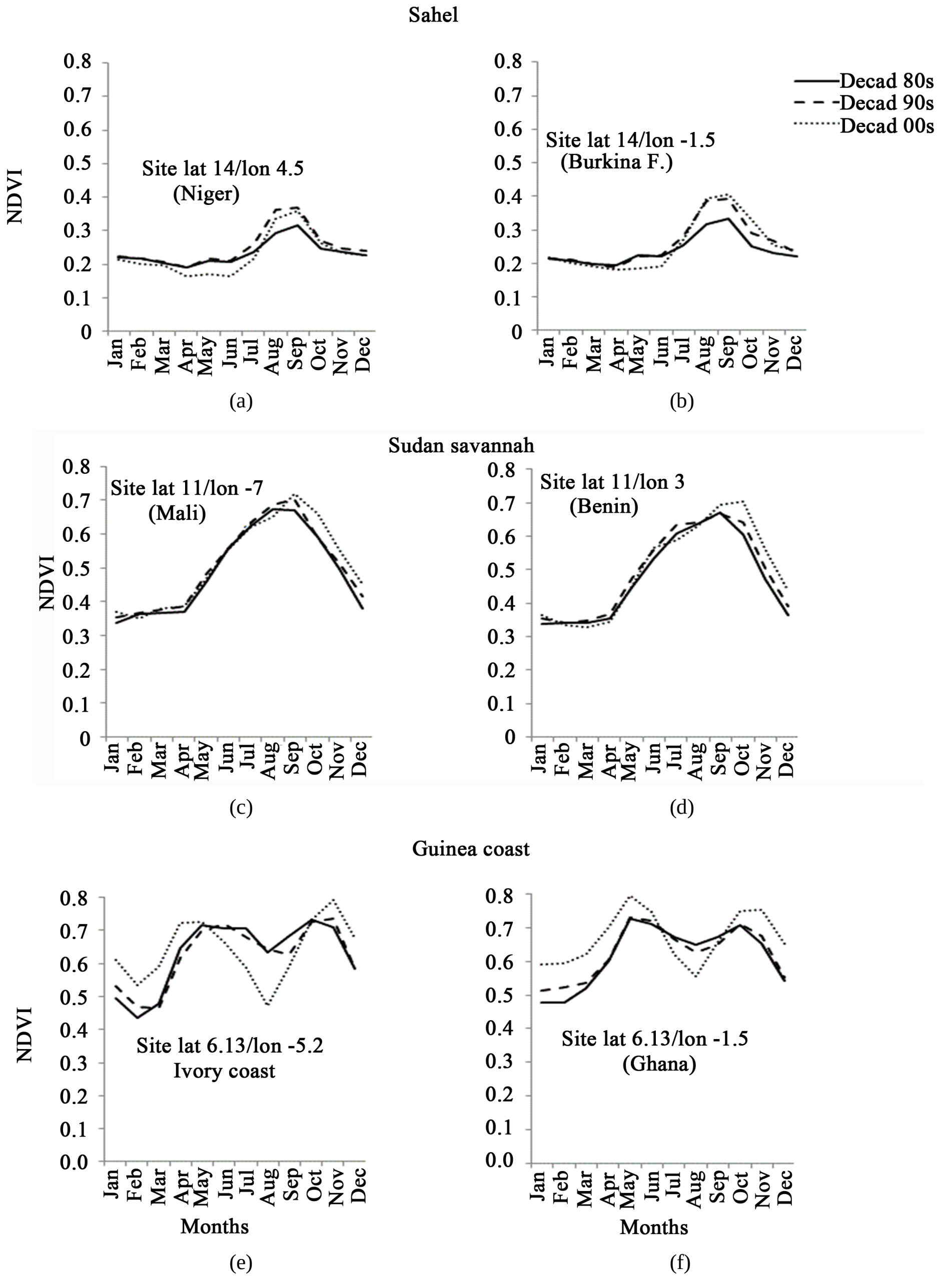
(c) (d)

(e) (f)

Figure 5. Decadal rainfall at the monthly timescale plotted for the six selected sites in the Sahel region ((a) Niger and (b) Burkina Faso), the Sudanian region ((c) Mali and (d) Benin) and the Guinea region ((e) Cote d'Ivoire and (f) Ghana).

The seasonal variability of NDVI is analysed over 1980s, 1990s and 2000s (**Figure 6**) at the six selected sites. Sahel and Sudanian savannah are characterised by NDVI unimodal seasonal cycles. However, the NDVI value is low over Sahel (<0.4) at both Niger and Burkina Faso sites (**Figure 6(a)** and **Figure 6(b)**). Comparing the three decades, the NDVI has decreased during the first semester in the decade 2000s. However, the peak of 1980s NDVI is the lowest. The vegetation has increased in July-August-September during the two last decades (1990s and 2000s). In the Sudanian savannah region, there is no significant change from January to July all over the three decades, while there is a significant re-greening from August to December in the decade 2000s The vegetation activity has extended in time. In the decade 2000s, while the core of the vegetation activity occurs in August, this is not true for rainfall (**Figure 6(c)** and **Figure 6(d)**). In the Gulf of Guinea region, the NDVI seasonal variability follows the bi-modal rainfall cycle. There is no important change between 1980s and 1990s. However, the seasonal variability seems to be more pronounced over the last decade. The vegetation growing process starts early in the last decade and end late. Decade 2000s is also characterised by strong drop of the NDVI in August (**Figure 6(e)** and **Figure 6(f)**).

The seasonal rainfall variability at the six selected sites over the three main climatic zones of West African region is observed in **Figure 7**. The Sahel rainfall cycle is unimodal with a peak in August (**Figure 7(a)** and **Figure 7(b)**). In the Sudanian Savannah region, rainfall seasonal variability remains unimodal with a peak in



(a) (b)

(c) (d)

(e) (f)

Figure 6. NDVI decadal mean averaged over months at six different points over Sahel region (a) Niger and (b) Burkina Faso, Sudanian Savannah regions (c) Mali and (d) Benin and Guinea regions (e) Cote d'Ivoire and (f) Ghana.

August of about 350 mm in Mali and 250 mm in Benin. Shifts in the rainfall cycles are identified in the last decades, especially in Mali (**Figure 7(c)**). The two selected sites over Gulf of Guinea coastal regions, *i.e.*, Cote d'Ivoire and Ghana, show bimodal rainfall cycles (**Figure 7(e)** and **Figure 7(f)**). These two rainy seasons occur between May through June and September through October.

Over the two Sahel sites, the difference between the three decades is mainly observed in Niger, which displays wettest conditions in the decade 1990s (approximately 200 mm in August) and driest conditions in the decade 1980s (approximately, 100 mm in August). This is also proposed by Hagos and Cook [44]. Also, a shift in the rainy season in analysing the Mali site was observed. According to Louvet et *al.* [45], this shift could be associated with a late onset and late secession of the rainy season, and decreasing rainfall during the core of the

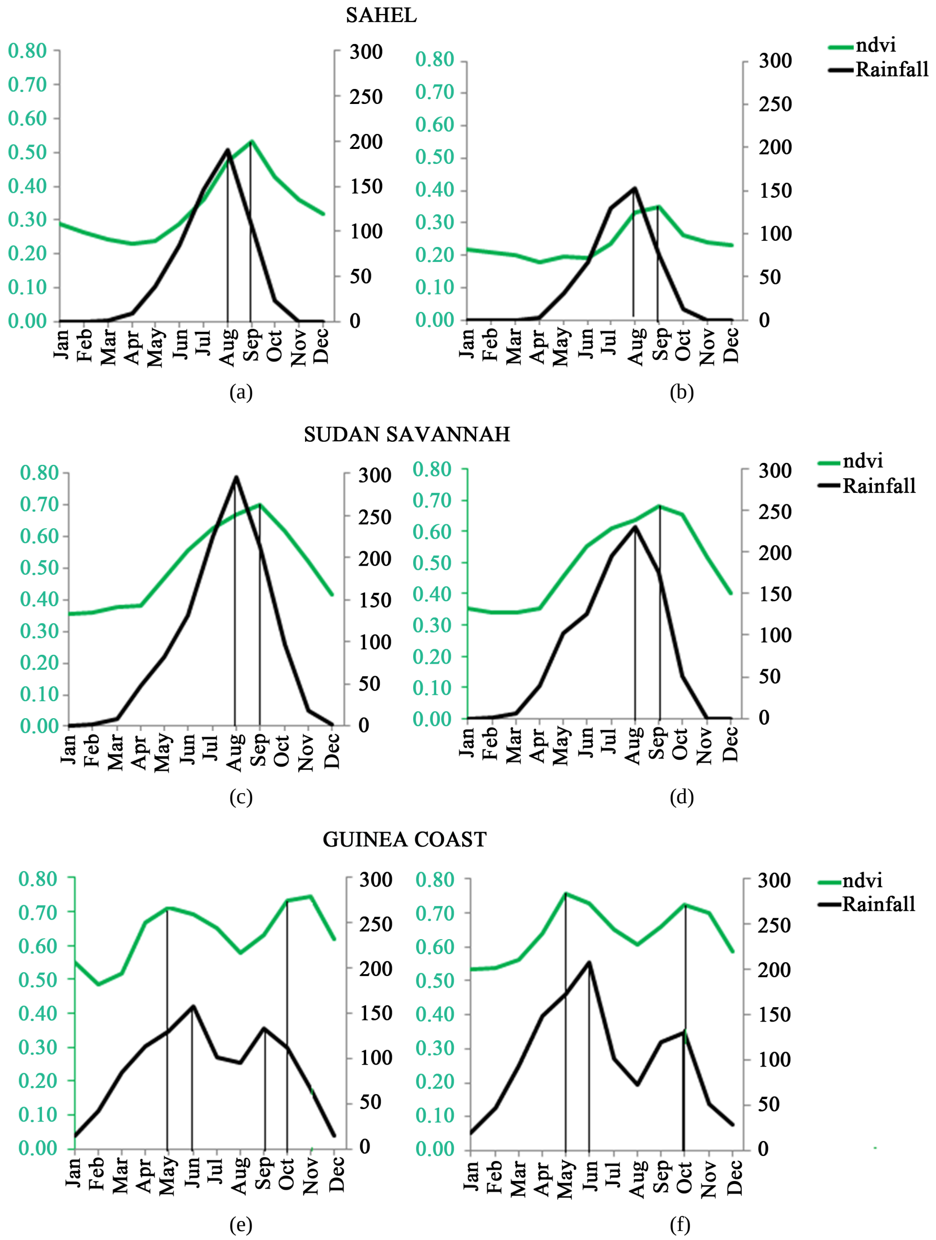


Figure 7. Thirty year Inter annual variability of Rainfall and NDVI showed over six selected sites in the Sahel region ((a) Burkina Faso and (b) Niger), the Sudanian Savannah region ((c) Mali and (d) Benin and the Guinea region ((e) Cote d'Ivoire and (f) Ghana)).

rainy season, *i.e.*, August. In Benin, rainfall is also slightly decreasing during August. Analysing different sites over the Gulf of Guinea coastal regions, which are characterized by two rainy seasons, a change have also been noticed. This change occurs in the decade 2000s; and is marked by enhancing rainfall during the second rainy season. However, as mentioned before, this change in rainfall seems to not influence the recent re-greening over the Gulf of Guinea coastal region.

4. Conclusion

Decadal variability in rainfall and the vegetation cover over West Africa is revisited from 1981 to 2010 using CRU gridded data, observed rain-gauges and the NDVI. Between the 1980s and 1990s, significant return to wet condition has been observed over West Africa. This is also noticed during the decade 2000s, with the exception of central Benin, western Nigeria. In decade 1990s, a re-greening of the central Sahel and Sudano-Sahel regions was detected, while there was a re-greening of western Sahel, Sudano-Guinea and Gulf of guinea coastal regions during decade 2000s. Over the Sahel, this is related to changes in annual rainfall, which are characterised by enhancing rainfall during the core of the rainy season (JAS) and an early start of the rainy season. These changes in seasonal rainfall also occur over the sudano-sahel regions. Over the Guinea Coast, such changes occur during the second rainy season, *i.e.*, the little rainy season. Enhancing rainfall, which was associated with an increased length of the little rainy season, therefore occurred during the last two decades. The seasonal NDVI variability shows generally the same evolution pattern compared to the rainfall, but during the last two decades, significant NDVI values were found one to two months after the end of the rainy season over the entire region. Correlations between rainfall and NDVI were significant over the Sahel, Sudanian savannah and northern part of Guinea Coast, but they become weaker in magnitude Guinea Coast from decade 1980s to 2000s meaning that in wetter conditions, there is no linear relationship between NDVI and rainfall over this region. It is quite clear from the result of this study that there is recovery of rainfall over some part of West African region after the long drought period. The increasing tendency observed in vegetation greenness is moving from the South to North. Although for the decade 1990s the re-greening process was mainly below latitude 10˚N however, in decade 2000s it has significantly reached latitude 12˚N. After the severe drought of the decade 1980s, the vegetation has been significantly re-greened over the Sudanian region between 8˚N and 15˚N in decade 1990s. The increase in vegetation over Sudanian region during this period could be due to the rainfall recovery which has started in decade 1990s and may have induced some vegetation cover recovery. This is however not the case in Guinea region where there were no changes were observed during this period. The comparison between decade 2000s and 1990s shows the persistence of significant positive changes in the coastal region below 8˚N.

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References

[1] Herrmann, S.M., Anyamba, A. and Tucker, C.J. (2005) Recent Trends in Vegetation Dynamics in the African Sahel and Their Relationship to Climate. *Global Environmental Change*, **15**, 394-404. http://dx.doi.org/10.1016/j.gloenvcha.2005.08.004

[2] Charney, J.G. (1975) Dynamics of Deserts and Drought in the Sahel. *Quarterly Journal of the Royal Meteorological Society*, **101**, 193-202. http://dx.doi.org/10.1002/qj.49710142802

[3] Sivakumar, M.V.K. (1992) Climate Change and Implications for Agriculture in Niger. *Climatic Change*, **20**, 297-312. http://dx.doi.org/10.1007/BF00142424

[4] Fensholt, R. and Rasmussen, K. (2011) Analysis of Trends in the Sahelian "Rain-Use Efficiency" Using GIMMS NDVI, RFE and GPCP Rainfall Data. *Remote Sensing of Environment*, **115**, 438-451. http://dx.doi.org/10.1016/j.rse.2010.09.014

[5] Omotosho, J.B. (1990) Onset of Thunderstorms and Precipitation over Northern Nigeria. *International Journal of Climatology*, **10**, 849-860. http://dx.doi.org/10.1002/joc.3370100807

[6] Rodwell, M.J. and Hoskins, B.J. (1996) Monsoons and the Dynamics of Deserts. *Quarterly Journal of the Royal Meteorological Society*, **122**, 1385-1404. http://dx.doi.org/10.1002/qj.49712253408

[7] Mathon, V. and Laurent, H. (2001). Life Cycle of Sahelian Mesoscale Convective Cloud Systems. *Quarterly Journal of the Royal Meteorological Society*, **127**, 377-406. http://dx.doi.org/10.1002/qj.49712757208

[8] Eltahir, E.A.B. and Gong, C. (1996) Dynamics of Wet and Dry Years in West Africa. *Journal of Climate*, **9**, 1030-1042. http://dx.doi.org/10.1175/1520-0442(1996)009<1030:DOWADY>2.0.CO;2

[9] Sultant, B. and Janicot, S. (2000) Abrupt Shift of the ITCZ over West Africa and Intra-Seasonal Variability. *Geophysical Research Letters*, **27**, 3353-3356. http://dx.doi.org/10.1029/1999GL011285

[10] Zeng, N. (2003) Drought in the Sahel. *Science*, **302**, 999-1000.

[11] Redelsperger, J.-L., Thorncroft, C.D., Diedhiou, A., Lebel, T., Parker, D.J. and Polcher, J. (2006) African Monsoon Multidisciplinary Analysis: An International Research Project and Field Campaign. *Bulletin of the American Meteorological Society*, **87**, 1739-1746. http://dx.doi.org/10.1175/BAMS-87-12-1739

[12] Lebel, T., Parker, D.J., Flamant, C., Höller, H., Polcher, J., Redelsperger, J-L., Thorncroft, C.D., Bock, O., Bourlès, B., Galle, S., Marticonera, B., Mougin, E., Peugeot, C., Cappelaere, B., Descroix, L., Diedhiou, A., Gaye, A.T. and Lafore, J.-P. (2011) The AMMA Field Campaigns: Accomplishments and Lessons Learned. *Atmospheric Science Letters*, **12**, 123-128. http://dx.doi.org/10.1002/asl.323

[13] Rasmussen, K., Fog, B. and Madsen, J.E. (2001) Desertification in Reverse? Observations from Northern Burkina Faso. *Global Environmental Change*, **11**, 271-282. http://dx.doi.org/10.1016/S0959-3780(01)00005-X

[14] Dardel, C., Kergoat, L., Mougin, E., Grippa, M. and Tucker, C.J. (2014) Re-Greening Sahel: 30 Years of Remote Sensing Data and Field Observations (Mali, Niger). *Remote Sensing of Environement*, **140**, 350-364. http://dx.doi.org/10.1016/j.rse.2013.09.011

[15] Harris, I., Jones, P.D., Osborn, T.J. and Lister, D.H. (2014) Updated High-Resolution Grids of Monthly Climatic Observations—The CRU TS3.10 Dataset. *International Journal of Climatology*, **34**, 623-642. http://dx.doi.org/10.1002/joc.3711

[16] Konaté, S. and Kampmann, D. (Eds.) (2012) Biodiversity Atlas of West Africa, Vol. 3: Cote d'Ivoire. Main, Abidjan and Frankfurt, 44-47.

[17] Janicot, S. and Fontaine, B. (1993) L'évolution des idées sur la variabilité interannuelle récente des précipitations en Afrique de l'Ouest. La Météorologie, Série 8, No. 1, 28-53. http://dx.doi.org/10.4267/2042/53332

[18] Nicholson, S.E. (2009) A Revised Picture of the Structure of the "Monsoon" and Land ITCZ over West Africa. *Climate Dynamics*, **32**, 1155-1171. http://dx.doi.org/10.1007/s00382-008-0514-3

[19] Le Barbe, L., Lebel, T. and Tapsoba, D. (2002) Rainfall Variability in West Africa during the Years 1950-90. *Journal of Climate*, **15**, 187-202. http://dx.doi.org/10.1175/1520-0442(2002)015<0187:RVIWAD>2.0.CO;2

[20] Lebel, T., Diedhiou, A. and Laurent, H. (2003) Seasonal Cycle and Interannual Variability of the Sahelian Rainfall at Hydrological Scales. *Journal of Geophysical Research*, **108**, 8389-8392. http://dx.doi.org/10.1029/2001JD001580

[21] Eischeid, J.K., Diaz, H.F., Bradley, R.S. and Jones, P.D. (1991) A Comprehensive Precipitation Dataset for Global Land Areas. DOE/ER-6901T-H1, US Department of Energy, Washington DC, [Available from National Technical Information Service, US Dept. of Commerce, Springfield], 81 p.

[22] Hulme, M. (1994) Global Changes in Precipitation in the Instrumental Period. In: Desbois, M. and Desalmand, F., Eds., *Global Precipitation and Climate Change*, Springer-Verlag, Berlin, 387-405. http://dx.doi.org/10.1007/978-3-642-79268-7_25

[23] New, M., Hulme, M. and Jones, P. (2000) Representing Twentieth-Century Space-Time Climate Variability. Part II: Development of 1901-96 Monthly Grids of Terrestrial Surface Climate. *Journal of Climate*, **13**, 2217-2238. http://dx.doi.org/10.1175/1520-0442(2000)013<2217:RTCSTC>2.0.CO;2

[24] Zhu, Z., Bi, J., Pan, Y., Ganguly, S., Anav, A., Xu, L., Samanta, A., Piao, S., Nemani, R.R. and Myneni, R.B. (2013) Global Data Sets of Vegetation Leaf Area Index (LAI) 3g and Fraction of Photosynthetically Active Radiation (FPAR)3g Derived from Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI3g) for the Period 1981 to 2011. *Remote Sensing*, **5**, 927-948. http://dx.doi.org/10.3390/rs5020927

[25] Wu, D.H., Wu, H., Zhao, X., Zhou, T., Tang, B.J., Zhao, W.Q. and Jia, K. (2014) Evaluation of Spatiotemporal Variations of Global Fractional Vegetation Cover Based on GIMMS NDVI Data from 1982 to 2011. *Remote Sensing*, **6**, 4217-4239. http://dx.doi.org/10.3390/rs6054217

[26] Jamali, S., Jönsson, P., Eklundh, L., Ardö, J. and Seaquist, J. (2015) Detecting Changes in Vegetation Trends Using Time Series Segmentation. *Remote Sensing of Environment*, **156**, 182-195. http://dx.doi.org/10.1016/j.rse.2014.09.010

[27] Tucker, C.J. (1979) Red and Photographic Infrared Linear Combinations for Monitoring Vegetation. *Remote Sensing of Environment*, **8**, 127-150. http://dx.doi.org/10.1016/0034-4257(79)90013-0

[28] Cracknell, A.P. (2001) The Exciting and Totally Unanticipated Success of the AVHRR in Applications for Which It Was Never Intended. *Advances in Space Research*, **28**, 233-240. http://dx.doi.org/10.1016/S0273-1177(01)00349-0

[29] Myneni, R.B., Hall, F.G., Sellers, P.J. and Marshak, A.L. (1995) The Interpretation of Spectral Vegetation Indexes. *IEEE Transactions on Geoscience and Remote Sensing*, **33**, 481-486. http://dx.doi.org/10.1109/36.377948

[30] Gray, T.I. and McCrary, D.G. (1981) Meteorological Satellite Data—A Tool to Describe the Health of the World's Agriculture. AgRISTARS Report EW-NI-04042, Johnson Space Center, Houston, 7 p.

[31] Holben, B.N. (1986) Characteristics of Maximum-Value Composite Images from Temporal AVHRR Data. *International Journal of Remote Sensing*, **7**, 1417-1434. http://dx.doi.org/10.1080/01431168608948945

[32] Nicholson, S.E., Tucker, C.J. and Ba, M.B. (1998) Desertification, Drought, and Surface Vegetation: An Example from the West African Sahel. *Bulletin of the American Meteorological Society*, **79**, 815-829. http://dx.doi.org/10.1175/1520-0477(1998)079<0815:DDASVA>2.0.CO;2

[33] Giannini, A., Saravanan, R. and Chang, P. (2003) Oceanic Forcing of Sahel Rainfall on Interannual to Interdecadal

Time Scales. *Science*, **302**, 1027-1030. http://dx.doi.org/10.1126/science.1089357

[34] Dai, A., Lamb, P.J., Trenberth, K.E., Hulme, M., Jones, P.D. and Xie, P. (2004) Comment the Recent Sahel Drought Is Real. *International Journal of Climatology*, **24**, 1323-1331. http://dx.doi.org/10.1002/joc.1083

[35] Lebel, T., Parker, D.J., Flamant, C., Bourles, B., Marticorena, B., Mougin, E., Peugeot, C., Diedhiou, A., Haywood, J.M., Ngamini, J.B., Polcher, J., Redelsperger, J.-L. and Thorncroft, C.D. (2010) The AMMA Field Campaigns: Multiscale and Multidisciplinary Observations in the West African Region. *Quarterly Journal of the Royal Meteorological Society*, **136**, 8-33. http://dx.doi.org/10.1002/qj.486

[36] Nicholson, S.E. (2005) On the Question of the Recovery of the Rains in the West Africa Sahel. *Journal of Arid Environments*, **63**, 615-641. http://dx.doi.org/10.1016/j.jaridenv.2005.03.004

[37] Lebel, T. and Ali, A. (2009) Recent Trends in the Central and Western Sahel Rainfall Regime (1990-2007). *Journal of Hydrology*, **375**, 52-64. http://dx.doi.org/10.1016/j.jhydrol.2008.11.030

[38] Evan, A.T., Flamant, C., Lavaysse, C., Kocha, C. and Saci, A. (2015) Water Vapor-Forced Greenhouse Warming over the Sahara Desert and the Recent Recovery from the Sahelian Drought. *Journal of Climate*, **28**, 108-123. http://dx.doi.org/10.1175/JCLI-D-14-00039.1

[39] Che, M., Chen, B., Innes, J.L., Wang, G., Dou, X., Zhou, T., Zhang, H., Yan, J., Xu, G. and Zhao, H. (2014) Spatial and Temporal Variations in the End Date of the Vegetation Growing Season throughout the Qinghai-Tibetan Plateau from 1982 to 2011. *Agricultural and Forest Meteorology*, **189-190**, 81-90. http://dx.doi.org/10.1016/j.agrformet.2014.01.004

[40] Anyamba, A. and Tucker, C.J. (2005) Analysis of Sahelian Vegetation Dynamics Using NOAA-AVHRR NDVI Data from 1981-2003. *Journal of Arid Environments*, **63**, 596-614. http://dx.doi.org/10.1016/j.jaridenv.2005.03.007

[41] Richard, Y. and Poccard, I. (1998) A Statistical Study of NDVI Sensitivity to Seasonal and Interannual Rainfall Variations in Southern Africa. *International Journal of Remote Sensing*, **19**, 2907-2920. http://dx.doi.org/10.1080/014311698214343

[42] Yuan, X., Li, L. and Chen, X. (2015) Increased Grass NDVI under Contrasting Trends of Precipitation Change over North China during 1982-2011. *Remote Sensing Letters*, **6**, 69-77. http://dx.doi.org/10.1080/2150704X.2014.1002944

[43] Wang, J., Rich, P.M. and Price, K.P. (2003) Temporal Responses of NDVI to Precipitation and Temperature in the Central Great Plains, USA. *International Journal of Remote Sensing*, **24**, 2345-2364. http://dx.doi.org/10.1080/01431160210154812

[44] Hagos, S.M. and Cook, K.H. (2007) Dynamics of the West African Monsoon Jump. *Journal of Climate*, **20**, 5264-5284. http://dx.doi.org/10.1175/2007JCLI1533.1

[45] Louvet, S., Paturel, J.E., Mahé, G., Rouché, N. and Koité, M. (2015) Comparison of the Spatiotemporal Variability of Rainfall from Four Different Interpolation Methods and Impact on the Result of GR2M Hydrological Modeling—Case of Bani River in Mali, West Africa. *Theoretical and Applied Climatology*.

[46] Pospichal, B., Karam, D.B., Crewell, S., Flamant, C., Hunerbein, A., Bockd, O. and Saıd, F. (2010) Diurnal Cycle of the Intertropical Discontinuity over West Africa Analysed by Remote Sensing and Mesoscale Modelling. *Quarterly Journal of the Royal Meteorological Society*, **136**, 92-106. http://dx.doi.org/10.1002/qj.435

[47] Gosset, M., Zahiri, E.P. and Moumouni, S. (2010) Rain Drop Size Distribution Variability and Impact on X-Band Polarimetric Radar Retrieval: Results from the AMMA Campaign in Benin. *Quarterly Journal of the Royal Meteorological Society*, **136**, 243-256. http://dx.doi.org/10.1002/qj.556